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BEHAVIORAL ECONOMICS

STEVEN R. HURSH

WALTER REED ARMY INSTITUTE OF RESEARCH

Economics, like behavioral psychology, is a science of behavior, albeit highly organized human behavior. The value of economic concepts for behavioral psychology rests on (1) their empirical validity when tested in the laboratory with individual subjects and (2) their uniqueness when compared to established behavioral concepts. Several fundamental concepts are introduced and illustrated by reference to experimental data: open and closed economies, elastic and inelastic demand, and substitution versus complementarity. Changes in absolute response rate are analyzed in relation to elasticity and intensity of demand. The economic concepts of substitution and complementarity are related to traditional behavioral studies of choice and to the matching relation. The economic approach has many implications for the future of behavioral research and theory. In general, economic concepts are grounded on a dynamic view of reinforcement. The closed-economy methodology extends the generality of behavioral principles to situations in which response rate and obtained rate of reinforcement are interdependent. Analysis of results in terms of elasticity and intensity of demand promises to provide a more direct method for characterizing the effects of "motivational" variables. Future studies of choice should arrange heterogeneous reinforcers with varying elasticities, use closed economies, and modulate scarcity or income. The economic analysis can be extended to the study of performances that involve subtle discriminations or skilled movements that vary in accuracy or quality as opposed to rate or quantity, and thus permit examination of time/accuracy trade-offs.

Key words: economics, demand, elasticity, open economies, closed economies, substitutes, complements, income, reinforcer value, response rate, choice, generalized matching, discrimination, observing response

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"Why economics?" is a question frequently asked of those interested in the relevance of economic theory for behavior analysis. The practice of looking to another discipline for useful ways to analyze behavior is certainly not without precedent. Consider Descartes' (1662/1965) hydraulic analogy, John Stuart Mill's (1843/1965) chemical analogy, Kurt Lewin's (1951) analogy to physical field theory, and, more recently, analogies to physics (Nevin, Mandell, & Atak, 1983) and control theory in engineering (McFarland, 1971). In contrast to these earlier theories, economic theory is more than an analogy to behavioral psychology; economics is also a science of behavior, albeit that of highly organized human behavior. Unlike behavioral psychology, it lacks a rigorous empirical base in controlled experimentation with individual subjects. This paper describes recent attempts to provide that base and the resulting benefits to behavioral psychology in terms of increased generality of our principles.

The value of economic concepts for behavioral psychology rests on (1) their empirical validity when tested in the laboratory with individual subjects and (2) their utility when compared to established behavioral

This paper is dedicated to the memory of Don Hake, a pioneer in the effort to close the gap between laboratory analysis of behavior and behavior in the natural environment. I wish to thank Richard Bauman and James Morrison for their assistance in conducting the experiments described and in the preparation of this manuscript. The views of the authors do not purport to reflect the position of the Department of the Army or the Department of Defense (para 4-3, AR 360-5). Reprints may be obtained from the author at Department of Medical Neurosciences, Division of Neuropsychiatry, Walter Reed Army Institute of Research, Walter Reed Army Medical Center, Washington, DC 20307.

concepts. Validity will be measured as the consistency of economic predictions with the results of behavioral experiments. Utility will be evaluated as a demonstrable difference between, on the one hand, economic concepts and the phenomena they describe, and, on the other hand, current behavioral principles. If it meets these criteria, behavioral economics can appropriately shape what we do in the future in the behavioral laboratory, shape our descriptions of behavioral processes, and affect the generality of our predictions.

THE VALIDITY AND UTILITY OF ECONOMIC CONCEPTS

Many of the concepts described here were developed as an outgrowth of other studies conducted at the Walter Reed Army Institute of Research. The subjects were monkeys that were housed in their test chambers, a practice that permitted multiple test sessions each day as well as continuous testing. It was not feasible or necessary to keep the animals at some prescribed weight (i.e., 80% ad lib); rather, their total daily ration was given during the course of a day's testing. The maximum ration or the length of the sessions was usually set to ensure an adequate rate of responding. Under these conditions, I confirmed the informal "lab lore" of this laboratory: To increase response rate, one increased the size of the fixed-ratio (FR) or variable-interval (VI) schedule, or decreased the size of the reinforcer. This relationship held true for conventional reinforcers such as food and water as well as for reinforcement by drug self-administration (e.g., heroin and morphine). This phenomenon appeared to contradict current theories of simple action (Catania, 1963; Herrnstein, 1970); certainly our manipulations reduced the amount of reinforcement, yet the rate of responding increased. This observation led to a more extensive experiment (Hursh, 1978) in which two monkeys (SM2 and SM3), housed in their experimental chambers, were studied. They were tested for about 100 min per day and received their

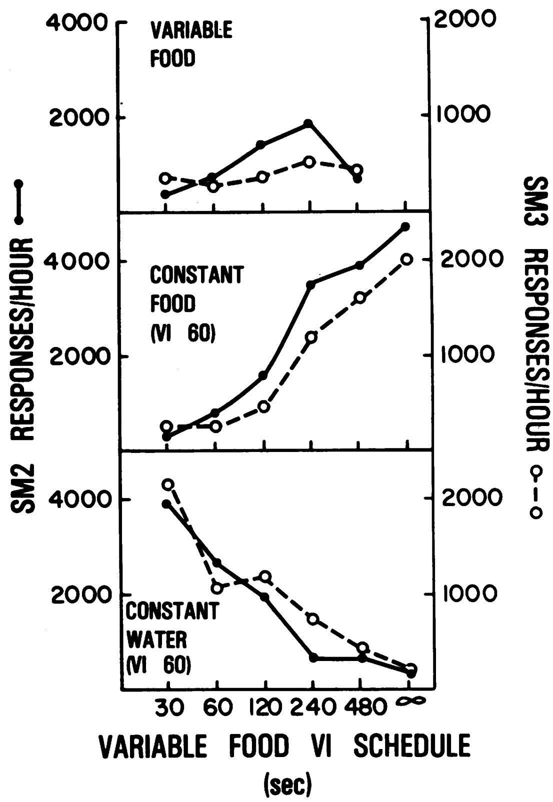

Fig. 1. Absolute response rate (responses per hr) of two monkeys (SM2, filled circles; SM3, unfilled circles) in a closed economy under three concurrent VI schedules shown as a function of the mean value of one of the schedules. Top panel: responsing on a variable VI schedule of food-pellet delivery as a function of the mean schedule value along the x axis. Middle panel: responding on a constant VI 60-s schedule of food-pellet delivery as a function of the value of the changing VI food schedule. Bottom panel: responding under the constant VI 60-s schedule of water delivery as a function of the value of the changing food schedule. Data are from Hursh (1978).

total ration of food and water during the sessions (a closed economy). The basic procedure was a three-lever concurrent schedule. Two schedules were held constant at VI 60 s, one providing single pellets of food and the other providing single squirts of water; the third VI schedule provided identical pellets of food and its mean value was varied in five steps from 30 s to 480 s.

Figure 1 summarizes the changes in response rate. Responding on the two food schedules (top two panels) generally increased as the VI schedules were lengthened (except

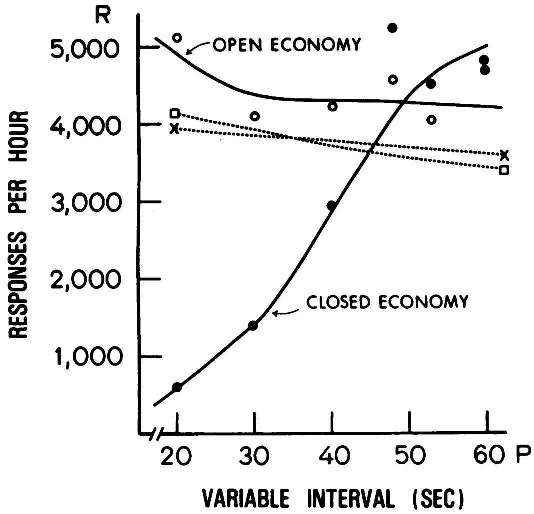

Fig. 2. Average absolute response rate (responses per hr) on VI food schedules of two monkeys in either a closed economy (filled circles) or an open economy (unfilled circles), shown as a function of the programmed mean VI duration (s). Average response rate and programmed VI value were calculated as the sum of performance and reinforcement from two separate concurrent VI schedules (see Hursh 1978, 1980). Also shown for comparison are the mean changes in response rate over the same range of VI values observed in two previous studies of pigeons in open economies, Catania (1963, squares) and Catania & Reynolds (1968, Xs).

SM3, variable food schedule). The greatest increase occurred under the constant VI schedule. Responding under the VI water schedule decreased as the VI food schedule increased (bottom panel).

These results showed that when subjects obtain their total daily food ration by responding during the test session, response rate is *inversely* related to rate of reinforcement. This relation is summarized in Figure 2, labeled "closed economy." The increase in responding for food could not be explained by appeal to either progressive deprivation effects across VI schedules or satiation within sessions; the increase in response rate occurred despite constant overall food intake (SM3) and even when only the first 15 min of each session were considered. The experiment was repeated (Hursh, 1978, Experiment II) with provisions to hold daily food and water intake constant and independent of responding during the sessions ("open economy," Hursh, 1980). Food responding decreased slightly across increases in VI schedule as indicated in Figure 2, labeled "open economy." Included in Figure 2 for comparison are dashed lines indicating the average change in response rate under similar VI schedules reported by Catania (1963, squares) and by Catania and Reynolds (1968, Xs) for pigeons held at 80% of their free-feeding weights (i.e., an open economy). These results parallel the open-economy data from the monkeys and implicate the manner of controlling sessions as an important variable. Other examples exist in the literature (e.g., Collier, Hirsch, & Hamlin, 1972; Findley, 1959) and other experiments with rats have extended it (see Hursh & Natelson, 1981). The distinction between open and closed economies has become common (see Brady, 1982; Collier, 1983; Delius, 1983; Lucas, 1981; Mellitz, Hineline, Whitehouse, & Laurence, 1983; Norborg, Osborne, & Fantino, 1983; Rachlin, 1982).

The economic concept of demand elasticity predicts these results (e.g., Samuelson, 1976; Watson & Holman, 1977); the inverse relation between response rate and reinforcement rate or probability is derivable from the concept of *inelastic demand* (Hursh, 1980). Inelastic demend specifies that large increases in price (increases in FR or decreases in probability) will produce small decreases in consumption. This minimization of consumption loss can be achieved only by increases in total expenditure—in this case, response rate. It can be shown that the same applies to increases in VI schedules because price and interval length are directly correlated (see Hursh, 1980, Figure 18). While VI schedules set a limit on consumption, obtained rate of reinforcement can vary with overall response output if the sessions are sufficiently long and if the subjects are not so deprived as to respond at nearly maximal rates. In the experiment just described, increases in response rate with decreases in reinforcer availability increased the delivered rate of reinforcement from about 50% to nearly 100% of the maximum available.

This kind of inelastic demand would be expected only in cases involving an essential commodity such as food and in which no other source of the commodity is available.

The direct relation between response rate and reinforcement rate or probability is derivable from the concept of *elastic demand*, which specifies that small increases in price (e.g., FR or VI schedule) will produce large decreases in consumption. In this case, total expenditure, or response rate, decreases with increasing schedule size. With essential commodities such as food, this would be expected when there is a substitutable supply as in an open economy. Elastic demand might also be expected of nonessential commodities such as brain stimulation or saccharin (see Figure 4).

A second implication of the experiment was the contrasting changes with food and water reinforcement. Referring again to Figure 1, the variable food schedule (top panel) was concurrent with, and served as the context for, responding under two constant VI schedules, one for food and one for water. Responding under the constant food schedule increased and responding under the constant water schedule decreased. These results contradict any choice theory that predicts contextual effects without regard to the nature of the reinforcers (see Herrnstein, 1970, 1974; Rachlin, 1973). This point is illustrated in Figure 3. In the top panel the ratio of Food 2 lever presses (P_2) to Food 1 lever presses (P_1) is plotted as a function of the ratio of Food 2 reinforcers (R_2) to Food 1 reinforcers (R_1), each in logarithmic units. The major diagonal indicates perfect matching; actual data are a close approximation, with a commonly reported tendency to "undermatch" (Baum, 1974, 1979; Myers & Myers, 1977). The bottom panel depicts the ratio of total food to water presses as a function of food to water reinforcers, again in log units. Here the distribution of responses is negatively related to the distribution of reinforcers, a case of countermatching. The nearly vertical function suggests that responses were distributed to food and water schedules in a way that minimized changes in the ratio of food to water consumption (*x* axis); stated another way, the subjects defended a certain "water balance." This was possible because in a closed economy, subjects have control of their daily intakes, even under VI schedules.

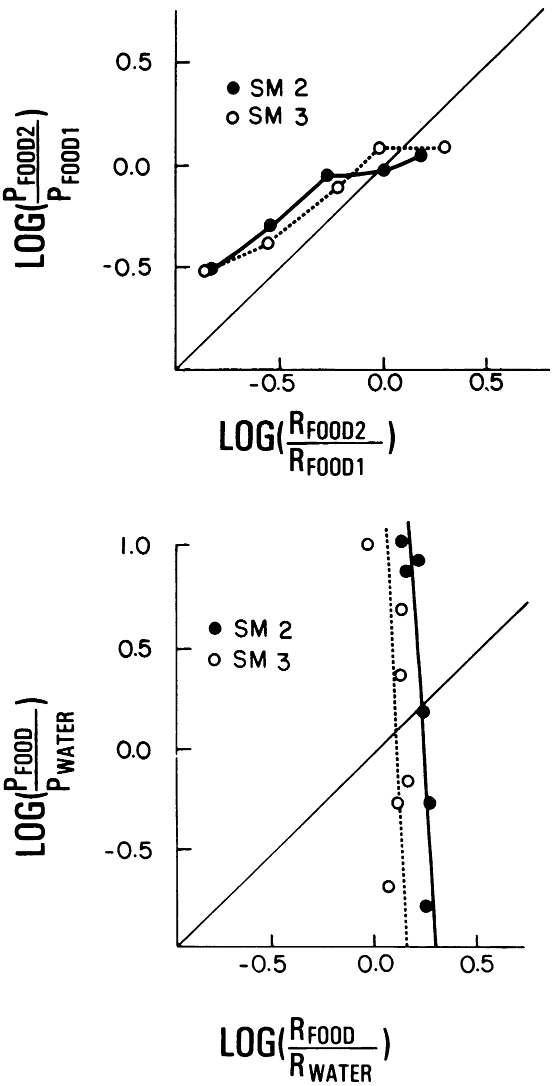

Fig. 3. Top panel: For two monkeys in a closed economy (SM 2, filled circles; SM 3, unfilled circles) the log ratio of performance (P) for Food 2 to Food 1, shown as a function of the log ratio of obtained reinforcers (R) from Food 2 to Food 1. Bottom panel: For the same subjects in the same experiment the log ratio of performance for Food (Food 1 plus Food 2) to Water, shown as a function of the log ratio of obtained food reinforcers (Food 1 plus Food 2) to obtained water reinforcers. Data are from Hursh (1978).

As one food schedule was restricted, responding increased in a way that minimized reductions in intake. As indicated above, percentage of available reinforcers actually obtained increased from about 50% to nearly 100%. At the same time responding for water decreased. This dynamic process had the effect of minimizing changes in the obtained ratio of food to water reinforcers through large counteradjustments in the ratio of food to water responses. The outcome was the strong countermatching seen in the bottom panel of Figure 3.

The function in the top panel illustrates the economic concept of *substitutes*. Food from Source 1 substituted for food from Source 2; as the quantity from Source 2 was reduced, responding to Source 1 increased (Hursh, 1980). In economic terms, strict matching presumes perfect substitutability and is a narrow subset of all choice possibilities accommodated by the economic theory of consumer demand (Rachlin, Kagel, & Battalio, 1980). The bottom panel shows an example of the economic concept of *complements*. Water complements the utility of food; as food becomes more abundant, responding for water increases relative to responding for food, thus minimizing changes in the ratio of the two levels of consumption (see Hursh, 1980). The generalized matching law (Baum, 1974, 1979) accommodates this kind of "countermatching" if the exponent takes negative values—in this case −10. Interestingly, Rachlin et al. (1980) have shown that generalized matching can be derived from economic utility theory (Barten, 1977; Samuelson, 1976; Watson & Holman, 1977) and, furthermore, utility theory provides a rationale for changes in the exponent in terms of "substitutability." Generalized matching, on the other hand, does not by itself lead to economic utility theory. The more general nature of utility theory opens the possibility of prediction of other novel phenomena beyond the scope of the generalized matching law. These are powerful indications that economic theory can serve as a useful guide to new behavioral phenomena.

Elasticity and Absolute Response Rate

The concept of elasticity has proven useful in subsequent research. Hursh and Natelson (1981) described an experiment in which three rats lived in two-lever test chambers. One lever provided, according to a VI schedule, two 0.5-s trains of electrical brain stimulation (EBS). The other lever provided, according to an identical VI schedule, a 45-mg food pellet. Across conditions of the experiment, both VI schedules were increased in mean length from 3 s to 60 s. In the first phase of the experiment the intensity of the EBS was chosen such that response rates for EBS and food were about equal at VI 15 s, labeled low current (LO). In the second phase, the intensity of the EBS was increased to a level just below that which elicited gross motor movements, approximately 2.5 times the low-current value, labeled high current (HI). The response-rate functions maintained by these different reinforcers are shown in Figure 4A. Response rates maintained by EBS (solid lines) and food (dashed line) are plotted as a function of VI value (note the log units). In both phases of the experiment (LO and HI current), responding for EBS was inversely related to VI value and responding for food was directly related to VI value. This result is surprising for two reasons. First, the two reinforcers did not maintain comparable performances in the face of comparable schedule changes. This, again, presents a challenge to any law of simple action that does not take into account the nature of the reinforcer (Catania, 1973; Herrnstein, 1970; see also de Villiers, 1977). Second, performance that produced food in this closed economy increased with decreasing reinforcer availability, similar to that seen with monkeys' food-reinforced responding in a closed economy but contrary to that seen for subjects working in an open economy (e.g., Catania, 1963; Catania & Reynolds, 1968).

These confusing distinctions in terms of response rate make sense in terms of elasticity of demand. The demand curves relating consumption to price (responses per rein-

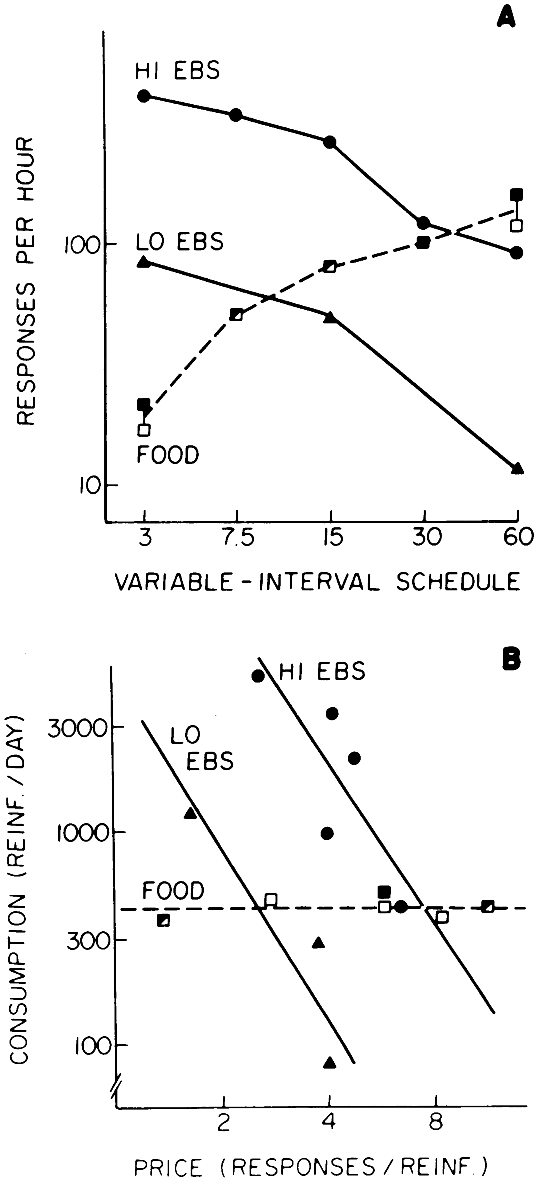

Fig. 4. Panel A: In log-log coordinates, average response rate (responses per hr) of three rats in a closed economy under two concurrent VI schedules of response-produced electrical brain stimulation (EBS, solid lines) and food pellets (dashed line), shown as a function of the mean value of both schedules. EBS was studied at two intensities indicated as low (LO) and high (HI). Data are from Hursh & Natelson (1981). Panel B: In log-log coordinates, the average consumption per day of EBS and food by the same three rats plotted as a function of the price, defined as the responses emitted per day divided by the reinforcers obtained per day. Lines of best fit are drawn through the points indicating the approximate slope or "elasticity" of these demand curves.

forcer) are shown in Figure 4B. Elasticity is defined as the slope of these functions plotted in log-log coordinates. Equal relative changes in consumption and price produce parallel changes in the demand curve plotted in log-log coordinates, independent of absolute level of demand. Figure 4B shows that food consumption declined only slightly with price, and demand therefore was inelastic. In contrast EBS consumption declined steeply with price, and demand therefore was elastic. Furthermore, increasing EBS intensity increased the level of *intensity* of demand but had little effect on elasticity of demand.

Elasticity as a Behavioral Concept

The next question is whether the concept of elasticity is distinct from other behavioral concepts or whether it is simply an economic name for a current behavioral term. Reinforcer *value* has been variously defined as the amount of reinforcement (Herrnstein, 1974) or the amount of behavior maintained by the reinforcer (e.g., Premack, 1965; Rachlin, 1971). According to either definition, when the level of EBS was increased in the second phase of the study by Hursh and Natelson (1981), EBS increased in value. The solid lines of Figure 4A show that responding during EBS was increased by a factor of about seven. Despite this increase in value, the elasticity of demand for EBS shown in Figure 4B was not altered and the downward slope of the demand curve with increasing price was identical under both low- and high-current conditions. Because value was manipulated without changing elasticity, these two concepts are distinct; value is more closely related to the level of consumption or intensity of demand while elasticity is a measure of the slope or rate of change in consumption.

Similarly, comparing the level of responding for EBS and food with minimal constraint (VI 3 s), one concludes that EBS was valued more than food at both intensities. Nevertheless, demand for EBS in the face of increasing constraint was more elastic than demand for food. Thus, a high level of consumption or performance for a commodity implying high reinforcer value does not imply inelastic demand in economic terms. The two terms are clearly distinct.

Elasticity is also distinct from the concept of response strength or momentum (Nevin et al., 1983). Although both are rate-of-change measures, response strength refers to changes in *response rate* as a function of some disrupter while elasticity measures changes in *consumption* as a function of price. A performance that declines less in the face of a disrupter compared to another performance is said to have greater strength. This is analogous to, but distinct from, saying that when consumption of one commodity declines less in the face of increasing price, compared to consumption of another commodity, it has less elastic demand. In some cases the two are mathematically related, as with changes in consumption and response rate under varying FR schedules. In other cases, response strength appears to provide a particularly fitting description of the results, as when response rate changes with increases in punishment intensity. In yet other cases, the concept of response strength seems less suitable than elasticity, as in the experiment with EBS and food. Here the same variable (VI size) increased the response rate for food and reduced the response rate for EBS. A similar contradiction is illustrated in Figure 2. In this experiment, the same variable (VI schedule) for the same reinforcer (food) produced opposite changes in response rate depending on the economic context, either open or closed.

These apparent contradictions are explicable in terms of demand and elasticity. Consumption of both EBS and food was reduced by the increase in VI schedule (see Figure 4B); the change was large for EBS (elastic) and slight for food (inelastic). The associated (and opposite) changes in response rate can be viewed as merely instrumental in supporting the more fundamental demand relationship. The difference in the rate of change in consumption (elasticity) between EBS and food is not a contradiction within this framework because what was consumed was different. Food could be viewed as an "essential" commodity with few substitutes, but EBS may be a "nonessential" commodity with many substitutes. Likewise, the difference between open and closed economies can be related to a more elastic demand curve in the open economy resulting from the availability of substitute food outside the constraints of the schedule. In both cases consumption was a downward sloping function of price; the availability of substitutes modulated the magnitude of that slope.

This experiment also indicated that elasticity is not a property of the reinforcer. It is a property of the demand curve that describes the adaptation process that can include the composition of the reinforcer as a controlling variable. Figure 2 indicated that monkeys working for food would, in a closed economy, show inelastic demand; in an open economy, they would show elastic demand.

Substitution, Complementarity, and Choice

The observation of complementarity between food and water (Figure 3, bottom panel) poses a problem for the standard behavioral theories of choice but is not surprising in relation to physiological studies of feeding and drinking. The standard physiological technique for studying this interaction is to deprive subjects of food or water and to observe changes in the intake of the other. Only several levels of deprivation are studied and intake of the other commodity is usually studied under free-feeding conditions (Bolles, 1961; Collier & Knarr, 1966; Kutscher, 1969).

Economic analysis provides a tool for studying in more detail this kind of interaction. By varying the price of food or water, one can alter consumption and plot a demand curve. At the same time, one can plot the "cross price" change in demand of the other commodity by monitoring parallel changes in its consumption. This method provides continuous functions relating, for example, water consumption to the price of food. Subsequent experiments alter the price of water, the total time available to work, or mix flavoring such as saccharin with the water to modulate the complementary relation.

Determining each demand curve requires the observation of consumption under a series of supply schedules. The most direct method is to use FR schedules because they directly set the price of the commodity. The usual practice in behavioral experiments is to study stable performance under each FR schedule, approximately 30 to 40 days per schedule. To obtain a demand curve with five points would take 5 to 6 months; additional experiments studying the effects of other variables could each take more than a year to complete. This method is impractical. Instead, we have adopted a rapid method for determining demand curves. After performance on a base FR value (e.g., FR 10) is stabilized, the schedule value is then increased by a fixed percentage each day up to some limit (e.g., FR 300). This procedure can provide a complete demand curve in 40 days with approximately 40 price levels. Changing a second variable, such as alternative commodities, deprivation level, or drug doses, becomes feasible, taking no longer than the usual time to conduct a behavioral experiment—4 to 6 months. It is an open question whether these demand curves have the same slope and elevation as demand curves obtained after stable performance at each ratio. This problem is of little concern, however, because the objective is to determine shifts in demand curves all deter-

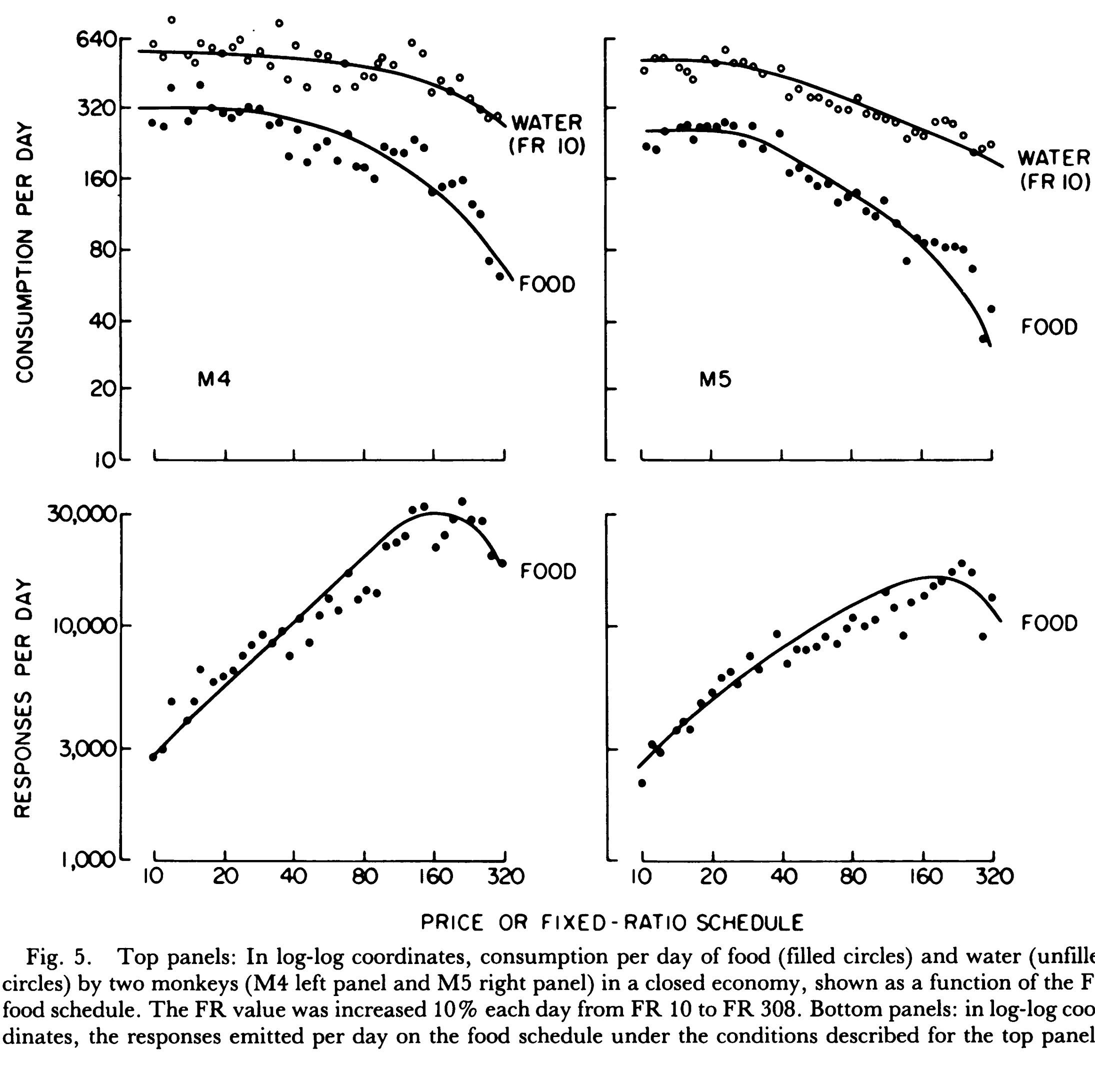

Fig. 5. Top panels: In log-log coordinates, consumption per day of food (filled circles) and water (unfilled circles) by two monkeys (M4 left panel and M5 right panel) in a closed economy, shown as a function of the FR food schedule. The FR value was increased 10% each day from FR 10 to FR 308. Bottom panels: in log-log coordinates, the responses emitted per day on the food schedule under the conditions described for the top panels.

mined using this rapid method of determination. Research so far indicates that excess variability is not a problem compared to the more traditional method.

Figure 5 displays the results of one such demand curve determination. The FR for food was increased by 10% each day from FR 10 to FR 308. Two monkeys served as subjects and had 24-hr access to both food and water. The top two panels show the demand curves for food of both subjects, along with the accompanying levels of water consumption. The demand curves for food showed increasing elasticity as the FR was increased. The curves are generally inelastic at prices less than approximately FR 200 and response rate increased with increasing price (shown in the bottom panels). The curves become elastic at higher prices and the response rate functions turn downward. Ratios higher than FR 308 were not studied because levels of consumption became dangerously low for these large animals. It would not be appropriate to describe behavior under these higher ratio as indicative of behavioral strain, however; response rate at FR 308 was well above the rate at FR 10.

Water consumption showed the expected complementary change downward as food consumption decreased. This was accompanied by a decline in water responding (not shown), a change entirely consistent with our physiological understanding of feeding and drinking but difficult to accommodate by any theory of choice that treats all reinforcers as qualitatively homogeneous. Were food and water equivalent reinforcers, an increase in FR for food should have increased water-reinforced responding and consumption of water.

Future studies with this method could arrange for a variety of alternatives besides water—saccharin, wheel running, nesting, or social-oriented behavior. One would expect a variety of cross-demand relations ranging from complementarity, as in this example, to substitution, as in cases in which the alternative is another food. In addition, the elasticity of demand for the target commodity should be sensitive to the degree of substitution available from other alternatives. One would predict a high degree of elasticity of demand for one food with another food source available and decreasing levels of elasticity as alternatives become less substitutable. More recent tests have extended the results shown in Figure 5. Saccharin-sweetened water instead of plain water was provided concurrently with food. The size of the food FR was increased in the same manner as described above. For both subjects the slope of the demand curve was indeed steeper or more elastic, as one would expect if sweetened water functioned as a partial substitute for food. Nevertheless, the saccharin consumption curve was not consistently different from the prior water consumption curve, providing no evidence for physiological substitution.

Complementarity of food and water may not require change in consumption. Following the clear case of complementarity shown in Figure 3, another experiment was conducted with provisions to increase the price of food without necessarily reducing the overall consumption. The procedure was similar to that reported by Hursh (1978) except that the three concurrent VI schedules for two foods and one water were all equal at VI 120 s. The price of one food was altered by imposing a terminal-link FR requirement prior to delivery of the food pellet. During this FR the levers and lights correlated with the other alternatives were inoperative and the session timer was halted so that this extra work did not count against total session time and consequently did not reduce the overall availability of food and water. The duration of each session was three hours. Because the three concurrent VI schedules were equal and access time to them was constant, total opportunities to eat and drink remained constant so long as some responding was maintained by all three schedules. The terminal-link FR for one food was varied in eight steps from FR 1 to FR 240. Except at FR 240, total consumption of food and water was constant. Figure 6 shows the changes in response rate plotted similarly to Figure 1. Each point is a mean of two replications. Of

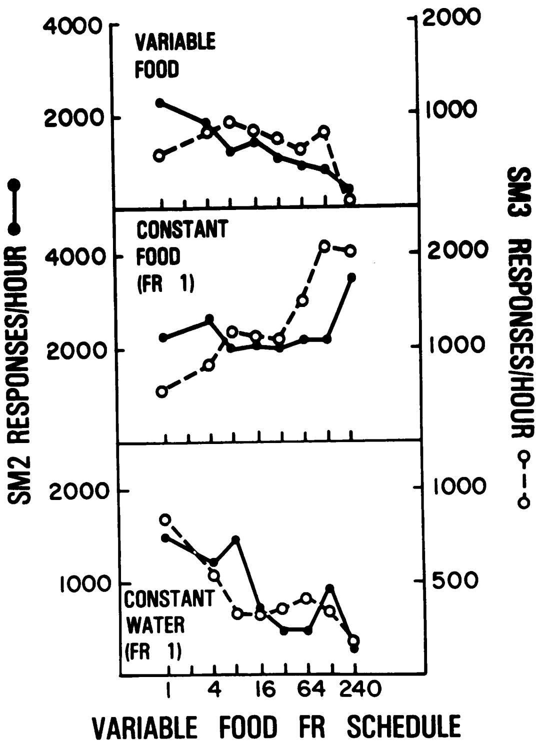

Fig. 6. In a manner similar to Figure 1, the absolute response rate (responses per hr) of two monkeys (SM 2, filled circles; SM 3, unfilled circles) working in a closed economy under three concurrent VI 120-s schedules, shown as a function of the terminal-link FR schedule (log scale) appended to one of the VI food schedules. The top panel shows performance under the VI schedule leading to the terminal-link FR schedule that varied in value as shown along the *x* axis. The middle panel shows performance under the VI food schedule that led to a constant terminal link FR 1. The bottom panel shows performance under the VI water schedule that also led to a constant terminal-link FR 1.

principle interest in the complementary change in water responding in the bottom panel. Although the decline is not as uniform and large as it was in Figure 1, complementarity was clear for both subjects even at FR values less than 240, which did not alter food and water consumption.

Food-reinforced responding varied in a manner indicative of mutual substitution between the two foods. One would expect a reduced tendency to respond on the alternative with the increasing FR terminal link (variable food), and an increased tendency to respond on the alternative with the constant FR-1 terminal link (constant food). One subject (SM2) showed the former tendency predominantly; the other subject (SM3) showed the latter tendency predominantly. In both cases, however, the distribution of food responses shifted away from the variable schedule toward the fixed schedule.

IMPLICATIONS FOR FUTURE RESEARCH

The economic concepts introduced so far have been validated in initial laboratory experimentation and, in addition, appear to describe relationships that have no parallel within the current behavioral vocabulary. In this sense these concepts are useful for describing and interpreting phenomena that lie outside the domain of current behavioral terminology. This section will describe the utility of economic concepts for broadening the generality of behavioral principles and the implications of those concepts for future research.

A Dynamic View of Reinforcement

The economic approach to behavior typified by emphasis on the demand curve encourages the researcher to view consumption or obtained rate of reinforcement as a major outcome of behavioral adaptation and to focus on the manipulated conditions of the experiment (e.g., fixed-ratio schedule or price, available substitutes, supplemental feeding) as the important controlling variables. Both response rate and reinforcement rate are products of a dynamic adaptation process and it makes little sense to explain the final equilibrium level of one in terms of the other. For example, to say that "the increased rate of reinforcement led to an increased rate of responding" is an inadequate way to describe a situation in which reinforcement and responding are mutually interdependent. This problem has by no means been ignored by behavioral researchers. The solution typically has been to interupt this interdependence with special procedures such as short sessions with constant deprivation (open economies) and interval-based schedules of reinforcement. Unfortunately, the result has been a behavioral theory that lacks generality to situations of mutual interdependence of these variables typified by the closed economy. The experimental results described so far show clearly that the distinction is significant. To the extent that the natural environment resembles a closed more than an open economy, a shift to a more dynamic approach to behavior analysis based on studies of performance in closed economies will be necessary for a general theory of behavior.

Explaining response rate in terms of the programmed schedule value is a form of "causation at a distance" and challenges our understanding of behavioral control. Nevertheless, remote causation may provide a simpler and more powerful explanation. A simple notion of proximal causation with independent and dependent variables that immediately contact one another does not readily accommodate a dynamic system in which the variables interact in response to outside manipulations. To view response strength as a direct product of reinforcement is very different from the economic account that views responding as dynamic adaptation to constraint that, in turn, determines rate of reinforcement or consumption. Elasticity is a measure of how sensitive consumption is to the imposed constraint, and by implication, of how responding adapts to that constraint. The economic view has much in common with other regulatory accounts (Dunham, 1977; Logan, 1964; McFarland, 1971; Staddon, 1979; Timberlake, 1984) and shares some of the same relations described in recent considerations of feedback processes in behavior analysis (Heyman & Luce, 1979; Prelec, 1982; Prelec & Herrnstein, 1978; Rachlin & Burkhard, 1978; Staddon & Motheral, 1978; see also Hursh, 1980).

The Closed Economy

In part, the economic approach encourages use of closed economies in the experimental analysis of behavior. I have previously defined a closed economy (Hursh, 1980) as an "ideal state when daily consumption is the result of the equilibrium of supply and demand" (p. 223) or daily consumption is solely the result of the subject's behavior in interaction with the schedules of reinforcement. An open economy is "any of a variety of experimental arrangements that provides at least a measure of independence between daily consumption and the equilibrium condition" (p. 223). These terms define a continuum of conditions that range from specific arrangements of between-session feeding and control of session length that link daily consumption and the equilibrium conditions to others in which daily consumption is totally independent of behavior under the test conditions. Notice that it is not between-session consumption per se that creates an open economy, but arrangements that make daily consumption independent of within-session performance. A brief period of post-session access to a commodity with relatively long periods of access during the session may not diminish the importance of the within-session performance for controlling the overall level of consumption, and the results from such situations may approximate those from a closed economy. Likewise, an experimental arrangement in which all food is obtained during the session could function like an open economy if the length of the sessions were modulated so that a constant amount of food was consumed regardless of response rate.

Extending our experimental horizon to include the closed economy situation is required to increase the generality of behavioral principles. The principles discovered in the open economy do not, of course, cease to operate in closed systems; processes such as shaping, discrimination, and contrast undoubtedly occur in both contexts. Yet, the closed economy involves a form of interdependence between performance and reinforcement that is largely absent in the open economy and, therefore, introduces an additional source of functional control. The relative importance of that control will probably depend in part on the nature of the performance and the reinforcer. We have seen that with food reinforcement the form of control is radically different from that seen in an open economy. Where appropriate, then, we must be willing to add new terms to our current vocabulary to accommodate these new forms of control.

The exact nature of the continuum from closed to open economy in procedural terms is a fundamental subject for future research. Future research may define or redirect our focus. For example, is it the availability of a substitute source of the commodity that is critical to defining an open economy? And is the delay between the end of the session and this between-session consumption important? Or is it the feedback relationship between response rate in the test session and daily consumption that is fundamental to defining a closed economy, regardless of substitution effects? Whatever that fundamental variable is, it should modulate the elasticity of demand for an essential commodity such as food from elastic (open) to inelastic (closed) and shift the function relating response rate to ratio or interval size from an inverse to a direct relation (see Figure 2).

Demand Curve Analysis

Future behavioral analyses will undoubtedly evolve a dynamic view of behavioral control mechanisms; the economic account is one example. Whether we borrow economic terminology or formulate a separate framework remains a question; regardless, the notion of a demand curve is useful as a description of one aspect of reinforcement. This approach will do more than alter the way we speak about behavior. Analysis of behavior in terms of the demand curve provides a convenient unifying framework for analyzing a variety of variables that are usually described as "motivational" in their effects on behavior. The advantage both experimentally and conceptually is that the demand curve and the parameters describing its level and slope (elasticity) are descriptions of "motivational" effects that avoid reference to hypothetical factors such as deprivation, value, strength, or probability. To be sure, some of these terms can be defined operationally, yet more often they are used as ad hoc explanations. In contrast, plotting results in terms of the demand curve can lead immediately to a parametric description of a subject's performance, avoiding unnecessary inference.

The two fundamental parameters of the demand curve are (1) its slope in log-log coordinates called *elasticity* of demand and (2) its elevation relative to the orgin—what I call *intensity* of demand. These two parameters are illustrated in Figure 4B, the demand curves for low- and high-intensity EBS and for food. The change in intensity of EBS current shifts the level or intensity of demand without altering elasticity; the change in reinforcer from EBS to food alters the slope or elasticity of demand. In a review of the research, tentative categories of variables that selectively influence either elasticity or intensity of demand can be identified. Those variables are discussed in the following two sections.

Elasticity of demand. At least four sorts of variables alter elasticity of demand. First, the nature of the commodity can determine the slope of the demand curve or how vigorously the subject's performance defends intake in the face of increasing price. The demand curves for EBS and food in Figure 4B illustrate this case (Hursh & Natelson, 1981). Another example was reported by Findley (1959) in which demand for food and water was inelastic, but demand for room illumination was elastic (see Hursh, 1980).

A second variable altering elasticity is the species of consumer. Boice (1984) compared demand for water by two species of packrats, one captured in a desert environment, the other captured in a more moist environment. He found that although the arid-habitat packrats drank large amounts of water when price was low (i.e., FR 2) compared to moist-habitat packrats, they drank very little water when price was high (FR 32) compared to moist-habitat packrats. Thus, the demand curve of water consumption was far more elastic for the arid-habitat packrats than for the moist-habitat packrats. This provided an experimental quantification of the natural observation that packrats from the driest habitats drink the most free-standing water, even though they have the least "need" for water as gauged by their consumption of water when it is scarce.

A third variable that alters elasticity is the availability of substitutes. Previously I described how availability of substitutes in an open economy can increase elasticity (Figure 5) and how the elasticity of demand for food may depend on the availability of a sweet-tasting alternative. Lea and Roper (1977) have illustrated how availability of sucrose can alter elasticity of demand for food.

The fourth category is the economic context discussed earlier—either open or closed. The effect of this variable on elasticity may be a subset of the previous variable, substitution, or it may involve other factors as well, such as feedback mechanisms. The differences in response rate between open and closed economies shown in Figure 2 are directly related to inelastic demand in the closed economy and elastic demand in the open economy (see Hursh, 1980).

Intensity of demand. The level or intensity of demand appears to be altered by at least two categories of variables. First, the level of deprivation can increase the level of demand. Meisch and Thompson (1973) reported demand curves for ethanol under food satiety or food deprivation. The demand curve obtained with food deprivation was uniformly shifted upward in relation to the curve under food satiation, indicating that food deprivation increased the intensity of demand for ethanol (see Hursh, 1980).

Second, the magnitude of reinforcement may alter the intensity of demand for some commodities. Figure 4A shows an upward shift in response rate correlated with an increase in brain stimulation intensity. The related demand curves show a similar shift in level or intensity shown in Figure 4B.

Characterizing new variables. The value of this approach goes beyond a mere categorization of past results. By conducting appropriate experiments to measure demand and by determining the slope and intensity parameters, we can characterize new variables that may have "motivational" effects. Examples of novel variables might be new drugs, chemical toxins, brain lesions or stimulation, and circadian or seasonal changes (Elsmore & Hursh, 1982). To illustrate this approach, consider the study of hypothalamic hyperphagia in monkeys reported by Hamilton and Brobeck (1964). They reported food consumption as a function of FR schedule for control subjects and brain-lesioned subjects either in the dynamic phase of weight gain or after stable obesity. These demand curves showed higher levels of food consumption at low prices (FRs) for the lesioned subjects compared to controls, but higher levels of consumption for controls at high prices. This result was considered an anomaly at the time and led to the idea of "finicky" behavior produced by hypothalamic lesions. However, in the context of variables that we now know alter the demand curve, it appears no more anomalous than many other variables that have similar effects on the demand curve. The effect of the lesion was to increase the elasticity of demand for food and was similar in effect to changing the nature of the reinforcer or its relationship to substitutable alternatives. In some manner, the lesion shifted the elasticity of demand for food in a direction toward the elasticity of demand for electrical stimulation of the hypothalamus (Hursh & Natelson, 1981). Studies of other "novel" variables will benefit by comparison to the effects of known variables on the parameters of the demand curve.

Theories of Choice

Research conducted so far within the economic framework indicates clearly that behavioral theories of choice must be extended to and tested within a context of heterogeneous reinforcers (e.g., Hursh, 1978; Hursh & Natelson, 1981; Lea & Roper, 1977; Rachlin, Green, Kagel, & Battalio, 1976). When the reinforcers offered for choice are functionally identical and substitutable, economic theory predicts the usual matching relationship between relative responding and relative consumption (Rachlin et al., 1980). Because nearly all behavioral work on choice has used identical reinforcers for the alternatives, the matching relation is usually found. However, when the reinforcers provided are not identical, various degrees of nonmatching or even countermatching are found (Hursh, 1978; Rachlin et al., 1976, 1980), because changes in consumption of one alternative are not accompanied by equal and opposite changes in consumption of the other when the two are not substitutes. That is the major implication of the results shown in Figure 3.

Future work with a variety of reinforcers will enhance our understanding of the many forms of reinforcer interaction. Neither economic theory nor any other theory can predict the form of interaction between two novel commodities. However, economic theory provides a broader descriptive framework for characterizing these interactions than does current behavior theory. Once a specific type of interaction is identified, economic theory can predict a variety of other relations. For example, if two commodities are found to be substitutes based on an analysis of cross-demand relations, it follows that elasticity of demand for one should depend on the availability of the other. If two commodities are found to be complements based on changes in price, it follows that a decrease in supply (i.e., longer VI schedule) or a decrease in package size (i.e., reinforcer size or concentration) should produce similar complementary changes. Much of this proposed work with complements will parallel past work with substitutes (see de Villiers, 1977, for a review).

So far, interactions among commodities have been characterized as substitution (e.g., food vs. food) or complementarity (e.g., food vs. water). This dimension of choice is not dichotomous, however. One would expect a variety of interactions between these extremes, including certain reinforcers that may be quite independent. Returning again to Figure 4, notice that when the intensity of EBS was increased, it had a dramatic effect on the level of EBS responding and consumption, but had virtually no effect on the level of food responding or consumption. Although food became relatively less valuable, absolute responding was unaffected (see Herrnstein, 1970). Much future work remains to fully explore the range of interactions that can occur, the variables that modulate them, and the "mutuality" of these interactions. For example, food consumption may not be as sensitive to the price of water as water consumption is sensitive to the price of food. Although this enterprise will undoubtedly complicate our theories of choice, simplicity ought not be purchased at the price of accuracy. Economic theory provides a relatively simple framework for expanding the range of interactions that can be addressed (Rachlin et al., 1976).

Experiments conducted so far (Hursh, 1978; Hursh & Natelson, 1981) also indicate that theories of choice should be tested within the closed economy, where differences in elasticity among various reinforcers are most apparent. For example, Figure 4 displays the difference between EBS and food in a choice situation. Although the two schedules of reinforcement were always equal, increasing scarcity (increasing the mean interval of both VI schedules) shifted the distribution of responding from a preference for EBS to a preference for food, an outcome that probably would not occur within an open economy, in which demand for food is elastic and responding decreases with increasing scarcity.

The effect of varying elasticity on choice was also revealed in an experiment by Elsmore, Fletcher, Conrad, and Sodetz (1980) in which scarcity was manipulated by varying the intertrial interval in a discrete-trial choice procedure. On each trial either food or an injection of heroin was made available by means of a short FR schedule. As the frequency of trials was reduced by increasing the time between trials, consumption of heroin was reduced greatly while consumption of food was largely conserved; the proportion of trials with a food choice increased as the opportunities to make a choice decreased. This finding was consistent with the greater elasticity of demand for heroin compared to food found in another experiment, and confirms again the importance of studying choice for distinctly different reinforcers in a closed economy.

The effect of scarcity has other fundamental implications for a behavioral theory of choice. The opportunity to obtain any of a set of commodities is constrained by *income*. If money is exchanged to obtain items, then total amount of money available sets the limit on consumption. If responses or time are expended, then limitations on total responding, either as time or number, limit consumption. Choice is the way an organism distributes a restricted income, be that time or money, across a range of commodities. The redistribution of income that occurs when income is restricted implies that the proportionality of responses to two alternatives is not solely dependent on the relative value of the commodities but also depends on the available income (see Luce, 1959). If we consider session duration in a closed economy as an income manipulation, this analysis predicts shifts in choice with session duration, provided the array of commodities spans a range of elasticities. Likewise, if we increase the price of a commodity with inelastic demand, the increase in expenditure for it will reduce available income for all other commodities. This could, in turn, generate redistributions of the available income among those commodities based on their elasticities of demand. This would predict that choice between any two stable commodities is not independent of the context of performance for other commodities even when the other commodities are neither substitutes nor complements. Interactions may occur as a result of changes in available income. Future experiments on choice must involve distinctly different alternative commodities to reveal the variety of interactions that can occur, either as a consequence of changes in price of the alternatives or as a result of changes in income.

Qualitative Changes in Performance

An economic analysis can be extended to performances that require subtle discriminations or skilled movements. Elsmore and Hursh (1982) have noted that when discrimination performances are studied in a closed economy, the observed decrease in accuracy of a performance in the face of some disrupter is, in part, related to the severity of food deprivation or the availability of other sources of food. It often seemed that subjects would preserve a relatively high level of accuracy by altering some other aspect of their performance, such as taking longer to make a choice. Thus, in some cases increases in latency more accurately reflected the difficulty of the problem than decreases in accuracy. This kind of time/accuracy trade-off can make it impossible to compare performances in different situations that might involve different economic constraints and different sorts of trade-offs. This has not been a major problem for work on stimulus control, discrimination, and signal detection, because economic constraints usually have been highly controlled. Yet, it may be that time/accuracy trade-offs are more the rule than the exception in more naturalistic settings, and any extension of theories of stimulus control will have to account for this sort of adaptation.

An extension of economic theory in this domain might take the following form. In many operant studies of discrimination, the subjects must emit an observing response to produce the sample discriminative stimuli. Let us modify the normal procedure slightly so that observing responses produce only brief presentations of the sample stimulus. As is usual practice, if the stimulus falls in one category, one type of response (e.g., a press on the left lever) is correct and produces food; if it falls in another category, a different response (e.g., a press on the right lever) is correct. Across conditions of the experiment, the two categories of stimuli are made more similar and the difficulty of the discrimination is increased. One would expect, of course, that the percentage of correct choices would decline. One would also expect that the number of discrete observing responses emitted would increase. With these two measures, a demand curve can be constructed. A correct response is the commodity of interest because only correct responses produce the reinforcer; percentage correct in this setting is equivalent to the rate of consumption in a single operant situation. The price of a correct response could be measured as the number of observing responses per correct response. The demand curve would display on the x axis the number of observing responses per correct choice, the price variable; and on the y axis, the number of correct responses per block of trials or percentage correct, the consumption variable. This function would have the expected negative slope with higher prices associated with lower numbers of correct responses. The degree of negative slope (elasticity) might serve to characterize the importance of this discrimination in the context of alternative performances.

This approach helps us analyze time/accuracy trade-offs. As a discrimination becomes more difficult or is disrupted by some external variable, latency to make a choice increases. In a sense, increased time is expended to preserve accuracy. By considering the observation time (latency) per correct response or by converting the latency dimension to discrete units of observation per correct response, we obtain an independent measure of difficulty in terms of the "price" of a correct response. When comparing performances from different economic contexts, we can analyze them in terms of the slope of the demand curve for correct responses, the "elasticity" of accuracy. When comparing the effects of different disrupters, we can distinguish between tasks of constant difficulty (constant observations per correct) and tasks of different difficulty that are masked by compensations (variations in observations per correct) that result in constant accuracy.

This analysis also permits us to scale percentage correct according to an independent measure of difficulty and eliminates the need for a priori judgment by the experimenter. This is usually not a problem for dimensions of stimulation that affect the subject as they affect us (such as sound or light intensity); it is a genuine problem with novel dimensions. For example, suppose we are interested in a disrupter variable such as circadian variations in discrimination performance (see Elsmore & Hursh, 1982). We observe changes in accuracy as a function of time of day. In order to plot these data to indicate a decline in accuracy with time of day, one needs to order the points; however, we have no a priori measure of "preferred" working times. The price measure based on observing behavior would provide just such a measure. A variety of other "disrupters" of discrimination performance could be similarly scaled and compared along this common dimension of price. Potential disrupters that could be studied include noise level, concurrent distractor tasks, noxious stimulation, sleep deprivation, drug administration, or brain lesions. An economic analysis in terms of "price equivalent units" provides a performance-based measure of difficulty or disruption that is independent of our observation of accuracy and serves as a convenient scaler.

SUMMARY

The value of economic concepts for behavioral psychology rests on their empirical validity when tested in the laboratory with individual subjects, and on their uniqueness when compared to established behavioral concepts. These criteria were addressed here by considering data relevant to the concepts of open and closed economies, elastic and inelastic demand, and substitution versus complementarity. The validity and utility of the demand curve and of the concept of elasticity of demand were illustrated by a consideration of the ways changes in elasticity of demand are related to changes in absolute response rate. Experiments were discussed that varied elasticity by altering the reinforcer or by altering the availability of substitutes. Demand elasticity was compared to the more conventional behavioral concepts of reinforcer value and response strength, and was found to be distinct from these.

To illustrate the economic concepts of substitution and complementarity, several studies were discussed, exploring choice among qualitatively different reinforcers. The results indicate that the commonly observed matching relation does not always hold in such situations. Demonstrations of complementarity illustrated the existence of "countermatching" and the need for either an expanded interpretation of the generalized matching law or a more economic model of choice that subsumes the matching relation as descriptive of choice among substitutable alternatives. Demand-curve analysis provides a direct empirical method for characterizing the effects of variables commonly described as "motivational." The two basic parameters of demand—elasticity and intensity—were considered, and categories of variables were proposed that seem to selectively alter these parameters.

With respect to future behavioral research and theory, the behavioral-economic approach suggests a characterization of reinforcement processes that departs from the standard view of unidirectional causation with independent and dependent variables. For example, theories that posit rate of reinforcement as a fundamental independent variable are replaced by concepts of dynamic behavioral adaptation whereby both performance and obtained rate of consumption are viewed as outcomes of adjustment to environmental constraints. Such a view is most important in closed economies, where there are strong interdependencies between rates of responding and daily consumption.

Finally, economic analysis is not limited to the study of simple operants; it can also guide our study of performances that involve subtle discriminations or skilled movements—performances studied in terms of accuracy or quality as opposed to rate or quantity. The focus here is not on the traditional notions of sensitivity and bias, but rather on a third process that we might call "disruption" of discrimination. Economic methods can be used to address time/accuracy tradeoffs and to scale disrupters of discrimination.

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